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14. ABSTRACT
This project integrated a series of new approaches to the investigation of the causes of water column variability in coastal regions. *In situ* sensors and satellite remote sensing provided time-series and spatial pattern information on physical, chemical, and biological processes in coastal waters. The *in situ* sensors were used for fixed-point time-series and for underway measurements from small boats. The satellite remotes sensing used AVHRR and SeaWiFS ocean color imagery. These studies were conducted in two very different regimes: one was the coastal waters of Rhode Island, and the other was in the region of Hong Kong. The results of this work have shown the influences of tidal mixing, meteorological conditions, river discharge, and biological processes on temperature, salinity, oxygen, pH, turbidity, and chlorophyll in coastal waters.

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WATER COLUMN VARIABILITY IN COASTAL REGIONS

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OBJECTIVES

The objective of this research is to understand the causes of temporal and spatial variability in coastal waters. Of primary interest are oxygen, carbon dioxide, suspended particulate matter (SPM), chlorophyll, temperature, and salinity. These properties were selected because their variability encompasses a wide range of processes such as (i) *in situ* photosynthesis, respiration, and decomposition of organic matter, (ii) air-sea gas exchange, (iii) response to meteorological conditions (solar radiation, wind velocity, heat exchange), (iv) physical processes such as tidal mixing, stratification, water mass variations, (v) runoff from land, and (vi) anthropogenic inputs. We seek to obtain a quantitative understanding of the physical, chemical, and biological processes that produce variability in coastal waters. The processes being investigated include the atmospheric forcing of water column properties, the effects of physical mixing and circulation, the biological uptake and release of nutrients and gases, and chemical reactions at phase boundaries. The information derived from this research will provide the basis to construct quantitative models of a range of properties in coastal waters and their variability.

APPROACH

We combined *in situ* sensor measurements with satellite remote sensing. Time series observations have been maintained near the entrance of Narragansett Bay since 1995. A spar buoy was deployed near the middle of the Bay in January 1997 with multi-depth sensors to measure changes in stratification and the vertical gradients. Two buoys with data telemetry and *in situ* chlorophyll sensors were deployed in 1999. A technique was devised to tow the sensors from a small boat to determine lateral variability, and to obtain sections of vertical profiles. A variety of methods were used to analyze the high-resolution observations and to model the processes that cause variability in coastal waters. We have used AVHRR remote sensing to determine sea surface temperature (SST) variations in coastal waters and to detect variations in suspended particulate matter. We used SeaWiFS ocean color remote sensing to relate surface chlorophyll, SPM, and optical properties to the results obtained from *in situ* sensor measurements and AVHRR images.

WORK COMPLETED

Magnuson, Woods, Andrews, Swanson, and Kester obtained continuous time-series of variability near the entrance of Narragansett Bay at the GSO pier with water column and meteorological measurements every 15 minutes from 1995 through the present. Magnuson and Kester completed a study of the Total Alkalinity to salinity ratio (TA/S) in waters of the Bay and the adjacent U.S. shelf and slope waters. Using this ratio we calculated the total CO_2 concentration, the partial pressure of CO_2, and the air-sea exchange of CO_2 from the *in situ* temperature, conductivity, and pH sensors. In January 1997 Andrews, Woods, and Kester deployed a spar buoy at a central location in Narragansett Bay to obtain time-series variations at multiple depths (1, 4, and 12 meters) to determine changes in stratification (Andrews, 1997). Swanson (1997) completed an M.S. thesis in which high-resolution time-series of chlorophyll fluorescence was investigated at the GSO pier. Sieburth and Kester developed the Horizontal Deployment Apparatus for the sensor sondes Kester and Woods conducted an intensive study of coastal variability in the western Pacific with colleagues in Hong Kong from August 1997 through January 1999.

Wendy Woods is completing her doctoral studies of water column measurements and satellite remote sensing (AVHRR and SeaWiFS) in the coastal waters of southern China (Woods and Kester 2000a, 2000b). Kester worked with Danling Tang of Hong Kong University of Science and Technology in studies of ocean color and SST remote sensing in the coastal waters of China and the South China Sea. Tang, Ni, Kester, and Müller-Karger (1999) published a study of a winter phytoplankton bloom phenomenon first discovered by Kester and Fox (1993) in the South China Sea (SCS) southwest of the Luzon Strait using CZCS ocean color data. We published a paper on the AVHRR and *in situ* time-series of Rhode Island coastal waters, that examines the seasonal warming of lower Narragansett Bay and Rhode Island Sound (Fox, Kester, Andrews, Magnuson, and Zoski, 2000). This paper combined AVHRR SST observations, our multi-depth moored buoy data, the GSO-dock time-series data, and measurements from a NOAA offshore weather buoy to show the relationship between water properties in a bay and in offshore waters during winter, spring, and summer. The AVHRR SST images were used to detect and characterize the front between waters of the Bay and those of the Sound.

Tang and Kester worked on a joint study with Wang Zhaoding and J.S. Lian of the Daya Bay, China, Marine Biological Research Station to characterize the thermal plume from the Daya Bay nuclear power plant using AVHRR SST images and shipboard data. A manuscript has been submitted to Estuarine, Coastal and Shelf Science based on this work (Tang, Kester, Wang, and Lian, 2001).

The Narragansett Bay, RI, time-series data obtained from 1995-2000 were compiled into a CD-ROM database for distribution to other investigators. A website was established in December 2000 to provide users access to the time-series data (http://www.gso.uri.edu/~dkester/nbay/index.htm). Our data have also been made available to the Distributed Oceanographic Data

Distribution System (DODDS) developed by Peter Cornillon. Our work to link *in situ* sensor data to satellite remote sensing has been enhanced by including shipboard measurements with a portable fiber optic spectrometer. This instrument consists of an Ocean Optics, Inc., four-channel spectrometer interfaced to a notebook computer. There are four CCD 2048-pixel detectors covering the wavelength range 190-860 nm. This instrument has UV-grade optics and we use UV-grade optical fibers. The spectra from up to four optical signals can be measured concurrently. In our work we measure the incident solar radiation and the upwelling radiation from the water column; by lowering a fiber with profiling sensors we obtain the spectral attenuation of solar radiation through the water column. The signals are measured with typical integration times of 5-100 msec depending on signal intensity and fiber diameter. These optical measurements provide ground-truth validation of the algorithms used to process SeaWiFS and MODIS satellite ocean color image data in optically complex Case 2 waters

RESULTS

The GSO pier time-series has demonstrated the relative importance of various processes that cause physical, chemical, and biological variability near the entrance of Narragansett Bay. The effects of solar radiation, wind velocity, lunar cycle tidal amplitudes, storms, and exchange with offshore waters are seen in the temperature, salinity, oxygen, and P_{CO2} variations. The magnitudes of variability over seasonal to diel and shorter time-scales have been determined. Net daily fluxes of oxygen and carbon dioxide gas exchange have been analyzed. The characteristics of the 1997 winter-spring bloom were resolved in detail (Magnuson, 1997).

The underway measurements with towed sensor systems along with measurements of the TA/S ratio in Gulf Stream and coastal waters provided a means to determine gas concentrations and fluxes in the Gulf Stream, across a warm core ring, and across the continental slope and shelf south of Narragansett Bay (Magnuson 1997).

The TA/S ratios in coastal waters, and their use to determine CO_2 system variables were presented by Magnuson (1997). An improved procedure for alkalinity titrations was devised in which the Gran plot endpoint becomes better defined with the purging of the CO_2 gas that builds up as seawater is acidified. We established the TA/S ratio for Narragansett Bay waters over an annual cycle.

The multi-depth time-series in central Narragansett Bay obtained with the spar buoy system produced major new insights into vertical stratification in the Bay (Andrews, 1997). During January 1997 the surface water temperature cooled from 6°C to less than 1°C over a two week period. The bottom waters also decreased in temperature during this period, but they lagged the surface cooling so that for about 50% of the time they were warmer (by about 1°C) and more saline than the surface. We observed a series of stratification events, several days in duration, that were broken up by storm and tidal mixing events. Vertical oxygen saturation gradients developed during each stratification event, showing the rapid response of phytoplankton to these periods of stratification. The spring warming of the Bay and importance of injection of offshore waters at depth into the Bay were seen during the period March through May 1997.

Fox and Kester examined sea surface temperature variations on the continental shelf of the northeastern U.S. using AVHRR satellite imagery with 1 km resolution. The satellite data were verified with NOAA offshore buoy surface temperatures; underway ship-of-opportunity measurements were used to characterize a region of upwelling or intensive vertical mixing on the Nantucket Shoals that was revealed by the satellite images. Woods and Kester used an (SPM) algorithm to identify episodic features of high SPM reflectance near Nantucket Island.

The surface waters in Narragansett Bay warm slightly faster than the bottom waters producing an increasingly stratified water column. A very close relationship exists between the bottom water warming rate in the Bay and the surface water warming rate in RI Sound. We concluded that the *bottom* waters in the Bay acquire their properties at the *surface* in the Sound, and they are then transported into the Bay beneath the Bay's less dense surface layer. This finding provides new evidence for the way in which offshore waters affect bays and estuaries.

Based on satellite data from 1978-1986 and historical hydrographic station data in the SCS we found that during the winter monsoon of most, if not all years, there is an upwelling process southwest of the Luzon Strait that brings nutrients into the euphotic zone and increases phytoplankton biomass. This phenomenon results in a region of winter-time high biological productivity in a region that is otherwise classified as being oligotrophic.

Several general conclusions can be derived from our work. Biological primary production and phytoplankton blooms vary with the amount of sunshine and cloud cover in both RI and Hong Kong. Water column stratification varies with the phase of the moon due to differences in neap and spring tidal amplitudes. Bloom events are relatively short in duration (3 to 5 days) requiring frequent measurements to reliably detect their occurrence and magnitude. We see the effects of runoff from major storm events in altering surface water properties. The gas exchange rates of O_2 and CO_2 are relatively slow in coastal waters; only during periods of wind speeds greater than 40 km/hr do we observe equilibration of these gases between surface waters and the atmosphere.

The fiber optic spectrometer along with our *in situ* measurements provide valuable ground truth information for the analysis of AVHRR SST, visible channel and near-infrared channel radiances, of SeaWiFS radiances, and as they become available those of the MODIS sensor onboard the Terra and Aqua satellites. These measurements can resolve the contributions of phytoplankton chlorophyll, suspended particle light scattering, and colored dissolved organic matter in the signals detected by satellite sensors. The fiber optic spectrometer has the following advantages: it is small and highly portable; it can be powered by a 12-volt battery; it collects high resolution spectral data over a wide wavelength range rapidly; it has no moving parts; by varying the integration time of the measurement over a range of 5-100 or more msec, it achieves considerable dynamic range; fiber diameters can be selected to achieve various sensitivities; it measures up to four sources concurrently. Unlike many other field radiometers, this instrument is not restricted to the wavelength bands of a particular ocean color satellite. The spectra we obtain can be used to "ground-truth" remote sensing reflectances from SeaWiFS, MODIS, OCS

(the Taiwanese ocean color satellite), AVIRIS (an airborne hyperspectral imager), and future ocean color instruments.

IMPACT

The results of this work are readily applicable to other coastal locations. The instrument packages, the integration of *in situ* and satellite data, and the formulation of a forecasting capability can be applied to other sites. It should be possible to make an initial assessment of the sensitivity of a new area to the basic forcing functions using satellite remote sensing. This assessment can be enhanced by a limited term deployment of *in situ* measurement systems. During the summer of 1999 we used our time-series observations along with our previous analyses of processes in RI coastal waters to provide predictions of the likelihood of phytoplankton blooms. These predictions were distributed to about 25 of our colleagues who are working in this area so they could use the information in their sampling and studies. By focusing this work on achieving a coastal water column forecasting capability, we have not only a useful product for practical applications, but we have a severe test of our understanding of the underlying processes. This research provides an improved basis to distinguish between natural variability and changes due to human activities in coastal regions.

TRANSITIONS

During FY97 this project led to commercialization of new technology and to applications in the western Pacific region. At the ONR-sponsored workshop MARCHEM '93 Kester (1993) summarized problems associated with under-sampling chemical variability in the ocean. A dialog was initiated with Dr. John McDonald of YSI, Inc. which led to our evaluation and subsequent use of their rapid-pulse dissolved oxygen sensor, as well as other sensor systems. Since then we have worked closely with YSI and Endeco/YSI of Marion, MA on the improvements and applications of their instruments for coastal oceanographic measurements. Experiments in 1995 onboard R/V Oceanus demonstrated the feasibility of towing the sensor sondes to obtain high resolution spatial measurements. During FY96 and FY97 our studies were conducted in close cooperation with Professor Emeritus John McN. Sieburth, who upon retiring from the GSO faculty in 1991, selected and set up a small and efficient coastal research vessel that is 24 feet in length. His R/V Melanitta has been a valuable resource for our research.

Our investigations required a new approach to measure lateral variability in coastal waters. Patchiness in plankton populations has been recognized for many years, and we found "patchiness" in 1-km resolution AVHRR SST images on a range of spatial scales from about 2.5 to 44 km in northeastern U.S. coastal and continental shelf waters. While there are several towable platforms such as the Canadian Batfish and the British AquaShuttle, they are expensive and require special winch systems. We devised a simple system to tow the sensor sondes, and to switch modes of operation from profiling at fixed stations to underway towing during transits. Sieburth developed a prototype HDA (Horizontal Deployment Apparatus) for the autonomous

sensor sondes. Endeco/YSI entered into an agreement with Sieburth to commercialize the HDA and make it part of their product line. This research, and our collaboration with Sieburth, resulted in an inexpensive means to obtain underway physical and chemical measurements from a small boat.

The technologies we are using are highly portable. In July 1996 Kester began collaborative work with investigators at the Hong Kong University of Science and Technology (HKUST). The sensor sondes, a laptop computer, and the HDA were easily transported to Hong Kong as hand luggage for field experiments in Hong Kong and nearby waters. HKUST established a satellite receiving station in 1995 in anticipation of second-generation ocean color remote sensing. They obtain 1-km resolution AVHRR and SeaWiFS imagery in the western Pacific from the Bo Hai to Indonesia. We conducted a joint study with investigators at HKUST to investigate variability in their region by coupling the *in situ* and remote sensing observations. In May 1997 Kester visited the Korea Oceanographic Research and Development Institute (KORDI) to work with Dr. Dong Young Lee on equipping a ship-of-opportunity vessel with a sonde for surface measurements during regular transits of the Yellow Sea between South Korea and China. The approach being used in this research can obtain information on coastal variability virtually anywhere in the world, and significant opportunities exist to carry out this type of work in the western Pacific.

RELATED PROJECTS

During FY97 the NOAA National Marine Fisheries Service laboratory in Narragansett and the Rhode Island Department of Environmental Management initiated a program to obtain long-term systematic measurements in Narragansett Bay. They, along with funding from the NOAA National Ocean Service, have provided us with support to establish additional buoys with sensor systems located in surface and near-bottom waters to enable observations of multi-depth time-series variability and the evolution of stratification at multiple locations within the Bay. These systems along with our time-series measurements near the mouth of the Bay allow us to determine the progression of phytoplankton blooms, the effects of freshwater input events, and the intrusions of offshore waters as they progress through the Bay.

A group of investigators engaged in physical, chemical, and biological studies in Rhode Island coastal waters have coordinated their efforts to provide a more comprehensive view of events and ecosystem responses. We have distributed "State of the Bay" assessments once or twice a week to 25 investigators who are affiliated with the University of Rhode Island, Brown University, the Naval Underwater Warfare Center – Newport, RI, the U.S. Coast Guard R&D Center -- Groton, CT, the NOAA National Marine Fisheries Service – Narragansett Laboratory, and the EPA Narragansett Laboratory. Our time-series data are providing a context in which other investigators can better plan and understand their studies of these coastal waters

Our ONR-funded research has been designed for applicability to a wide range of coastal environments and we have pursued this work in Rhode Island and Hong Kong coastal waters. Information gained from the time-series measurements has prompted considerable interest. We worked with several investigators to establish an observing system in RI waters with an initial

focus on Narragansett Bay. An EPA EMPACT project in which we are a partner provided three additional time-series measurements systems near the head of Narragansett Bay in the urban area of Providence, RI.

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